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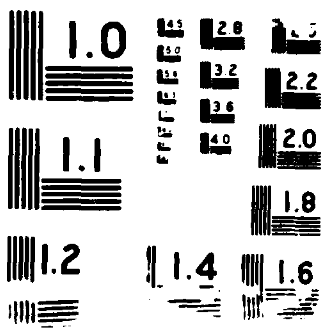
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THE DYNAMIC BEHAVIOR OF A TURBULENT BOUNDARY LAYER SUBJECTED TO A SHOCK-INDUCED SEPARATION

Final Technical Report

By

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This report is the Final Technical Report for ARO Contract DAAG29-85-K-0255, "The Dynamic Behavior of a Turbulent Boundary Layer Subjected to a Shock-Induced Separation," funded during the period 11/15/85 to 11/14/87. The three major aims of ~~the~~ contract (as stated in the original proposal) were: (1) to study the instantaneous behavior of the interaction; (2) to investigate the variations in separation bubble shape and size; and (3) to study the relaxation of the boundary layer far downstream of the interaction. The Contract was originally scheduled to be completed over a three-year period. The contract was terminated at the end of two years at the discretion of the Army Research Office. The reduced funding has affected mainly the completion of the third aim, the study of the relaxation behavior.

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1. SUMMARY

This report is the Final Technical Report for ARO Contract DAAG29-85-K-0255, "The Dynamic Behavior of a Turbulent Boundary Layer Subjected to a Shock-Induced Separation," funded during the period 11/15/85 to 11/14/87. The three major aims of the contract (as stated in the original proposal) were: (1) to study the instantaneous behavior of the interaction, (2) to investigate the variations in separation bubble shape and size, and (3) to study the relaxation of the boundary layer far downstream of the interaction. The Contract was originally scheduled to be completed over a three-year period. The contract was terminated at the end of two years at the discretion of the Army Research Office. The reduced funding has affected mainly the completion of the third aim, the study of the relaxation behavior.

2. PROGRESS ON CONTRACT OBJECTIVES

The detailed work statement for the three year program given in the original proposal (submitted September 1984) was as follows:

YEAR I:

(a) Preliminary measurements in the interaction zone.

(b) Measurements in the reattachment zone.

(c) Initial development of analytic models for unsteady shock wave/boundary layer interactions.

YEAR II:

(a) Measurements designed to characterize the instantaneous shape of the separation bubble.

(b) Preliminary work in the active control of the separation bubble.

(c) Design and construction of model and test section for new facility. This model and test section will be used to study the relaxation behavior far downstream of the interaction.

(d) Further development of analytical models.

YEAR III:

(a) Experimental work on relaxation behavior in new facility.

(b) Further work on actively controlled separation bubble.

(c) Further development of analytical models.

The proposal was funded with a starting date of 11/15/85. Only the first two years were funded. The progress achieved in this period is as follows:

YEAR I, Tasks (a) and (b) have been completed. The results were presented at the AIAA 25th Aerospace Sciences Meeting (see Reference 1). These results included mean flow and turbulence measurements at four principal stations upstream, within, and downstream of the interaction zone. The reduced data, with complete annotation, have been transcribed in standard format on magnetic tape, and the tape is available upon request from the principal investigators. The measurements will form part of the NATO data base due to be published by AGARD in 1988 (see Reference 2).

YEAR I, Task (c) has been completed. Two models for the unsteadiness of shock-wave boundary layer interactions have been suggested. The first model proposes that "the large fluctuations of the relative motions at various positions of the large structures of the incoming boundary layer may cause the shock-wave unsteadiness and the spanwise rippling of the shock wave" (from Reference 3)*. The second model proposes that in addition to the mechanism of the large scale boundary layer structure, Taylor-Goertler-like longitudinal vortices form due to concave curvature, and that these unsteady vortices contribute to the spanwise wrinkling of the shock front (see Reference 1). At present, both models seem possible, although our preliminary efforts have been based on the first model. In this effort, we are pursuing some fundamental studies of vortex motions interacting with shock sheets. The results are not yet ready for publication.

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*Please note that the acknowledgement in this reference is in error: it should read that ARO Contract DAAG29-85-K-0255 supported the analysis of the experimental results, not "the preparation of (the) paper."

YEAR II, Task (a) has been completed. Simultaneous measurements were made using fluctuating wall-pressure transducers and hot-wire anemometer probes. The preliminary results were reported in Reference 1, and the final results are given in M. Selig's M.Sc. thesis, submitted in February 1988 (Reference 4). The required 15 copies of this technical report accompany this Final Technical Report.

YEAR II, Task (b) has been completed. In fact, the active control of the separation bubble using periodic mass-injection at the wall (the originally proposed acoustic perturbation proved to be ineffectual) has been extremely rewarding. Flow visualization (Reference 4) and measurements (Reference 5) have already provided strong evidence that periodically varying the size of the separation bubble has little influence on the character of the shock-wave unsteadiness. This observation confirms our concept that it is the upstream boundary layer (and possibly an unsteady Taylor-Goertler vortex system) that controls the flow unsteadiness. We have observed that spectacular changes in flow structure can be achieved by injection of mass-flux equivalent to only 10% of the freestream mass flux (injected through a slot of width to 0.1 δ_o). As long as the mass is injected at the most effective location, the average position of the shock wave can easily be moved one boundary layer thickness upstream, thereby doubling the size of the separation bubble. Finding this location is most critical, and our investigation has covered four locations, four frequencies of injection and four mass-flux rates. We have obtained a large data base, and the results are summarized in Reference 4. Given the large number of parameters available for the dynamic control of the unsteady interaction, we feel sure that the optimal control strategy still remains to be found. Nevertheless, the current

indications appear to be very promising for this technique to be effective for active control, and to become a fundamental research tool in the investigation of the dynamic response of unsteady interactions.

YEAR II, Task (c). The new Low Turbulence Variable Geometry (LTVG) test facility has been plagued by delays during construction, and the commissioning trials are only now in progress. The delays were caused by the need to divert personnel from the construction to repair several major compressor breakdowns which occurred during the last year. Tunnel schedules were not seriously affected but the LTVG facility construction was severely delayed. Further delays were caused by unexpected turnovers in research staff, affecting Drs. K. C. Muck, J. Andreopoulos, J. H. Watmuff and Mr. M. S. Selig. To compensate for these delays, it was requested that Year II, Task (c), be held over till the following year and form part of the revised work statement for Year III. Since the third year option was not exercized, Year II, Task (c) was not commenced.

YEAR II, Task (d) is now suspended. The progress was discussed above under Year I, Task (c). No results are yet available for publication.

3. PROGRESS ACHIEVED IN ADDITION TO CONTRACTED OBJECTIVES

In addition to the progress achieved in the tasks specifically listed in the work statement, considerable contributions have been made in areas listed in Section 2 of the original report under the heading "Proposed Experimental and Analytical Work." The progress includes the use of multiple wall-pressure transducers, the development and interpretation of time series analysis for multiple-channel data, the application of conditional sampling criteria, phase-averaged measurements based on shock position, and stroboscopic highspeed imaging techniques (see References 1 to 5).

Furthermore, we have spent considerable effort in trying to improve hot-wire techniques for the particularly severe conditions experienced in the present experiment. Strain-gaging effects can be especially severe, and a theoretical study of hot-wire anemometry has revealed that this may be partially caused by electronic instabilities in the anemometer feedback circuit. The results were published in Reference 6. Some further work was reported recently in finding methods for reducing these undesirable effects (Reference 7). The required 15 copies accompany this Final Technical Report.

Multiple hot-wire probes appear to be too fragile for the particular flowfield under study, and we have thus far been unsuccessful in getting even a double wire probe to survive downstream of the interaction. Further development is still in progress since we feel these measurements are extremely important for improving our understanding of the flow behavior.

The development of thin hot-film gages for shock-wave boundary layer interactions has thus far met with little success. These gages were not available

for use on this contract. Similarly, LDV and RDV techniques are not yet available to us because the required additional funding has not been found.

<u>REFERENCES</u> (all references except #2 acknowledge ARO support)

1. M. S. Selig, J. Andereopoulos, K. C. Muck, J.-P. Dussauge and A. J. Smits, "Simultaneous wall-pressure and mass-flow measurements downstream of a shock-wave/turbulent boundary layer interaction." Presented at the 25th Aerospace Sciences Meeting, Reno, NV, January 1987, <u>AIAA Paper 87-0550</u>.

2. H. H. Fernholz, A. J. Smits, J.-P. Dussauge and J. P. Finley, (Eds) "A survey of measurements and measuring techniques in rapidly distorted compressible turbulent boundary layers," NATO AGARDograph, to be published 1988.

3. J. Andreopoulos and K. C. Muck, "Some new aspects of shock-wave/boundary-layer interactions in compression-ramp flows." <u>Journal of Fluid Mechanics</u>, Vol. 180, pp. 405-428, 1987.

4. M. S. Selig, "Unsteadiness of shock-wave/turbulent boundary layer interactions with dynamic control," M.Sc. Thesis, Dept. Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, February 1988.

5. M. S. Selig and A. J. Smits, "Flow visualization of periodic mass injection in supersonic turbulent boundary layers," *Paper EI4, 39th Annual Meeting, Division* of Fluid Dynamics, American Physical Society, November 1987.

6. J. H. Watmuff, "High order effects in the frequency response of the constant-temperature hot-wire anemometer." Presented at <u>ASME Conference on Thermal Anemometry</u> at Cincinatti, Ohio, June 1987.

7. J. H. Watmuff, "Increasing the frequency response of constant temperature hot-wire systems for use in supersonic flows," AIAA Paper 88-0421, January 1988.

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